GPS Meteorology

Presented by

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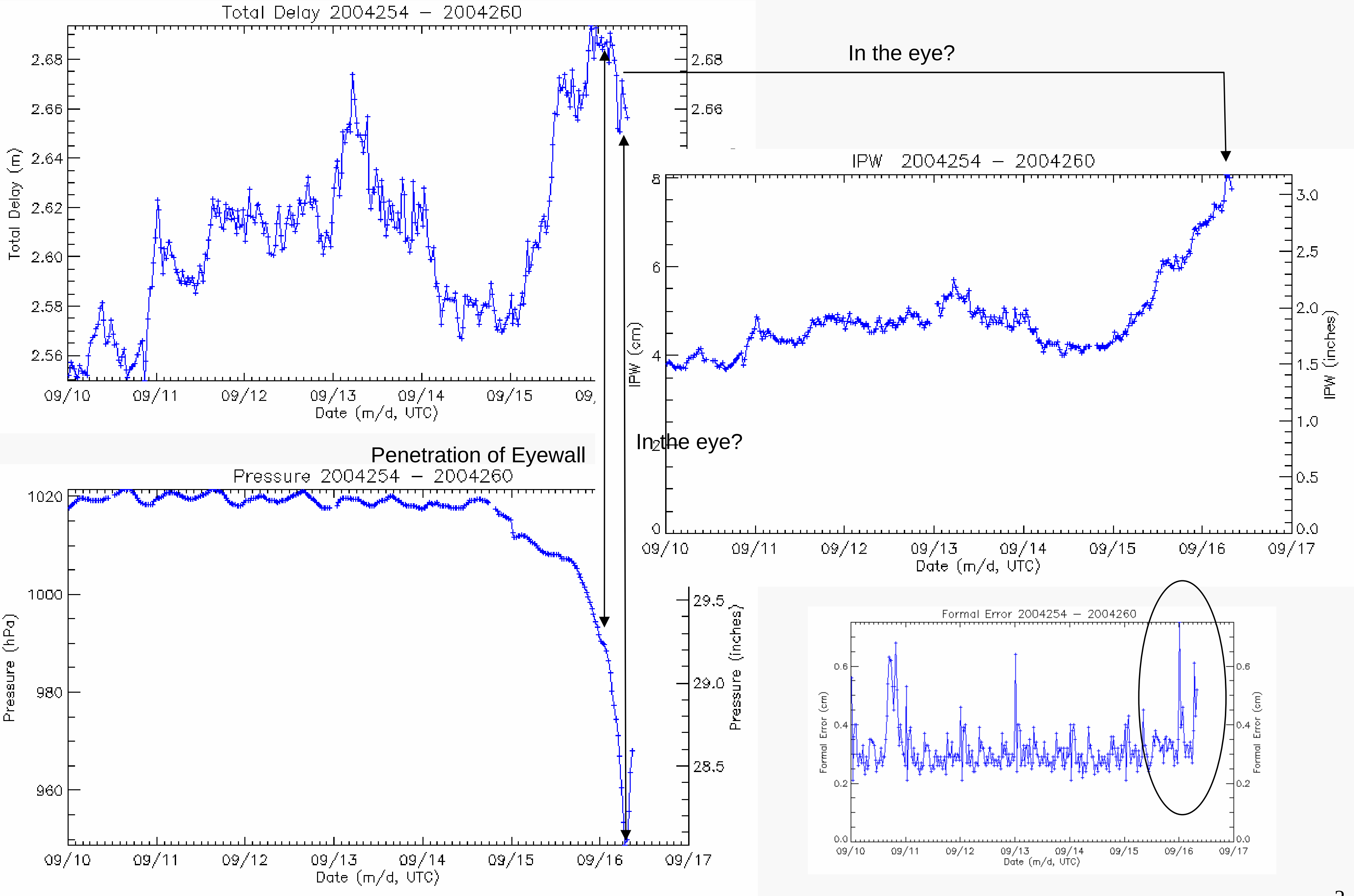
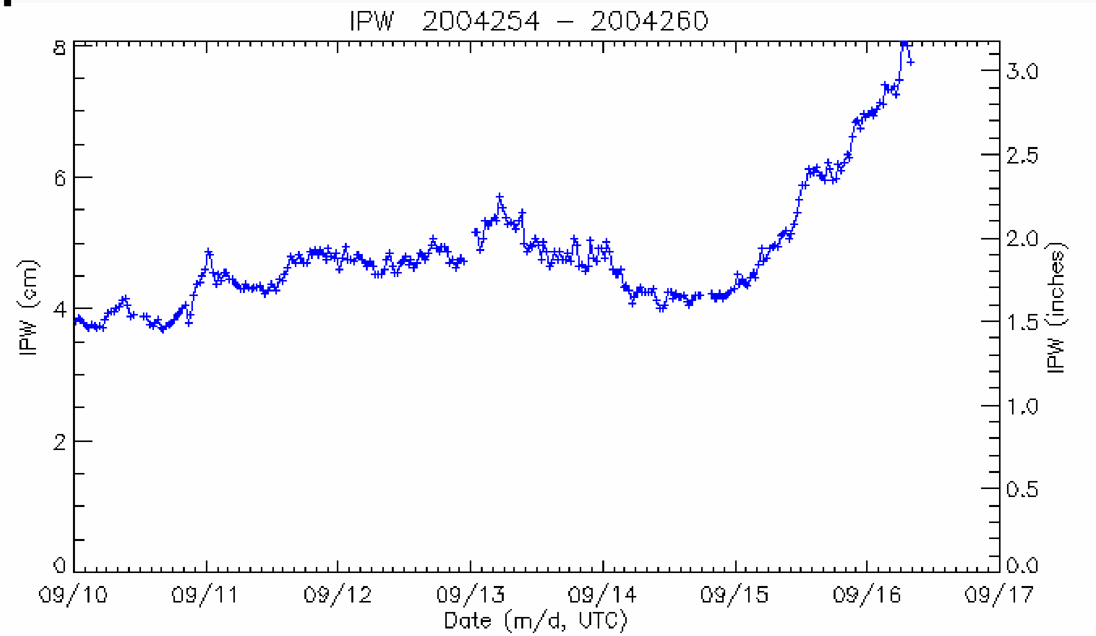
CGSIC U.S. States and Localities Session

Long Beach, California
September 21, 2004

Landfall of Hurricane Ivan

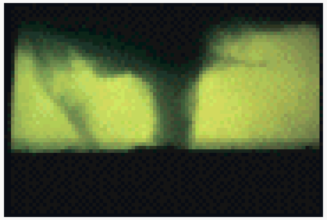
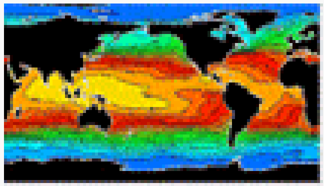


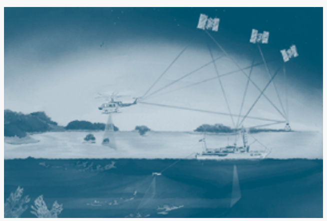
Why is This Observation Important?



- GPS is truly an all weather system.
- NDGPS is tough!
- ZTD estimation accuracy under the most severe conditions tested.
- NASA aircraft observation of PW enrichment in eye confirmed.

GPS Applications Within NOAA

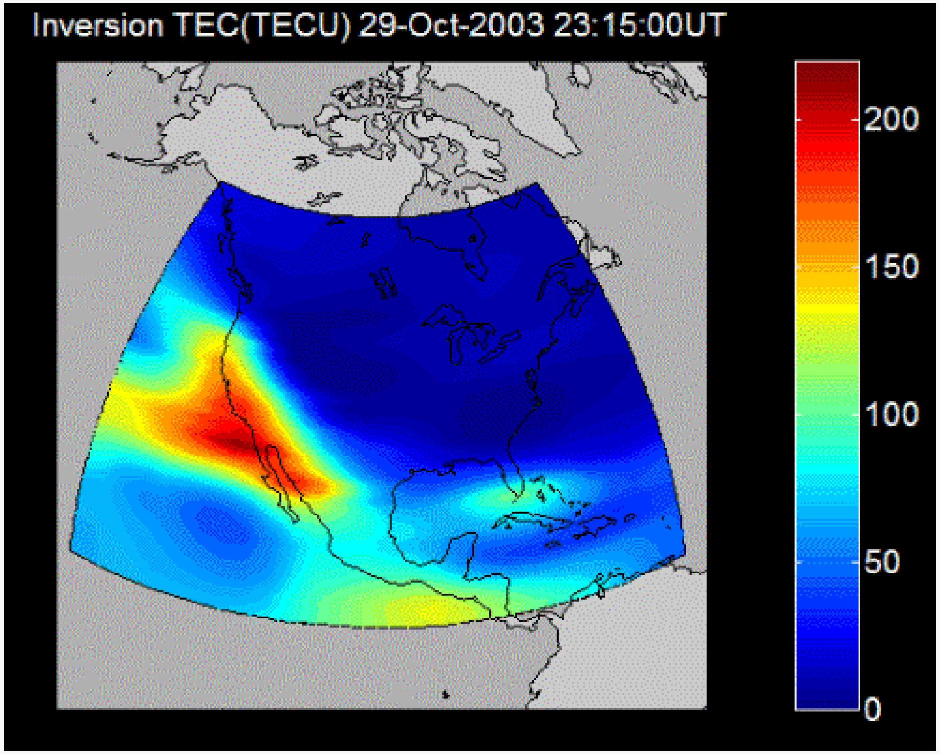
- NOAA, the National Oceanic and Atmospheric Administration within the U.S. Department of Commerce, is the federal agency responsible for atmospheric monitoring and prediction on time scales ranging from minutes and hours, to decades and longer in the case of climate.
- Another part of NOAA's mission is to promote commerce and safe transportation. It shares this mission with other federal agencies including the U.S. Departments of Transportation, Defense, and Homeland Security.
- Common among all these activities is the use of GPS for a growing number of conventional and non-conventional applications related to NOAA's mission.
- One such application is meteorology.

Introduction

- Since the removal of Selective Availability (SA), signal delays caused by the Earth's atmosphere dominate the GPS error budget.
- From a meteorological perspective, the reason why differential survey accuracy degrades with distance is because the radio-refractive properties of the ***ionosphere*** and ***troposphere*** become less correlated with distance and time.
- Under certain circumstances, the constituents of the atmosphere responsible for these signal delays:
  - free electrons in the ionosphere,
  - temperature, pressure, and water vapor in the troposphere

  vary greatly in very short periods, resulting in large errors and rapid changes in GPS positional accuracy.

- These circumstances are usually associated with space and tropospheric weather events, e.g.
  - geomagnetic storms in the upper atmosphere, and
  - weather events in the lower atmosphere ranging in scale from tropical storms to thunderstorms.

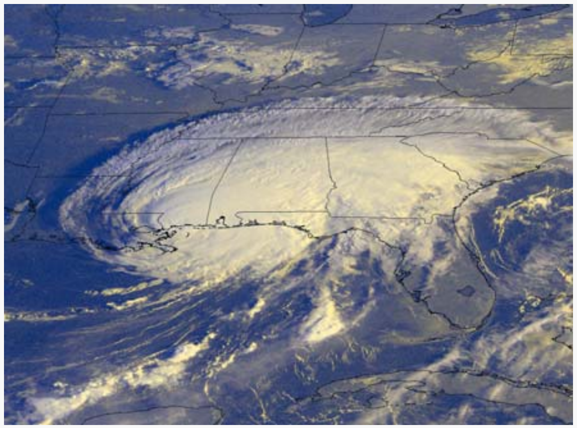


Weather Forecasting

- Successful weather forecasting requires three things:
  - observations of critical parameters;
  - techniques to analyze these observations;
  - physical models to make predictions.
- Current weather observing systems do not have the temporal and spatial resolution needed to make significant improvements in short-term (localized) weather events.
- This is especially true when it comes to observations of free electrons in the ionosphere (a tracer for geomagnetic activity) and water vapor in the lower atmosphere.
- The remainder of this presentation will concentrate on the lower atmosphere where most of the water vapor in the atmosphere resides.

Water Vapor in the Atmosphere

- Water vapor is one of the most important components of the Earth's atmosphere.
- It is the source of clouds and precipitation, and an ingredient in most major weather events.
- In its gaseous phase, water moves rapidly through the atmosphere, redistributing energy through evaporation and condensation.



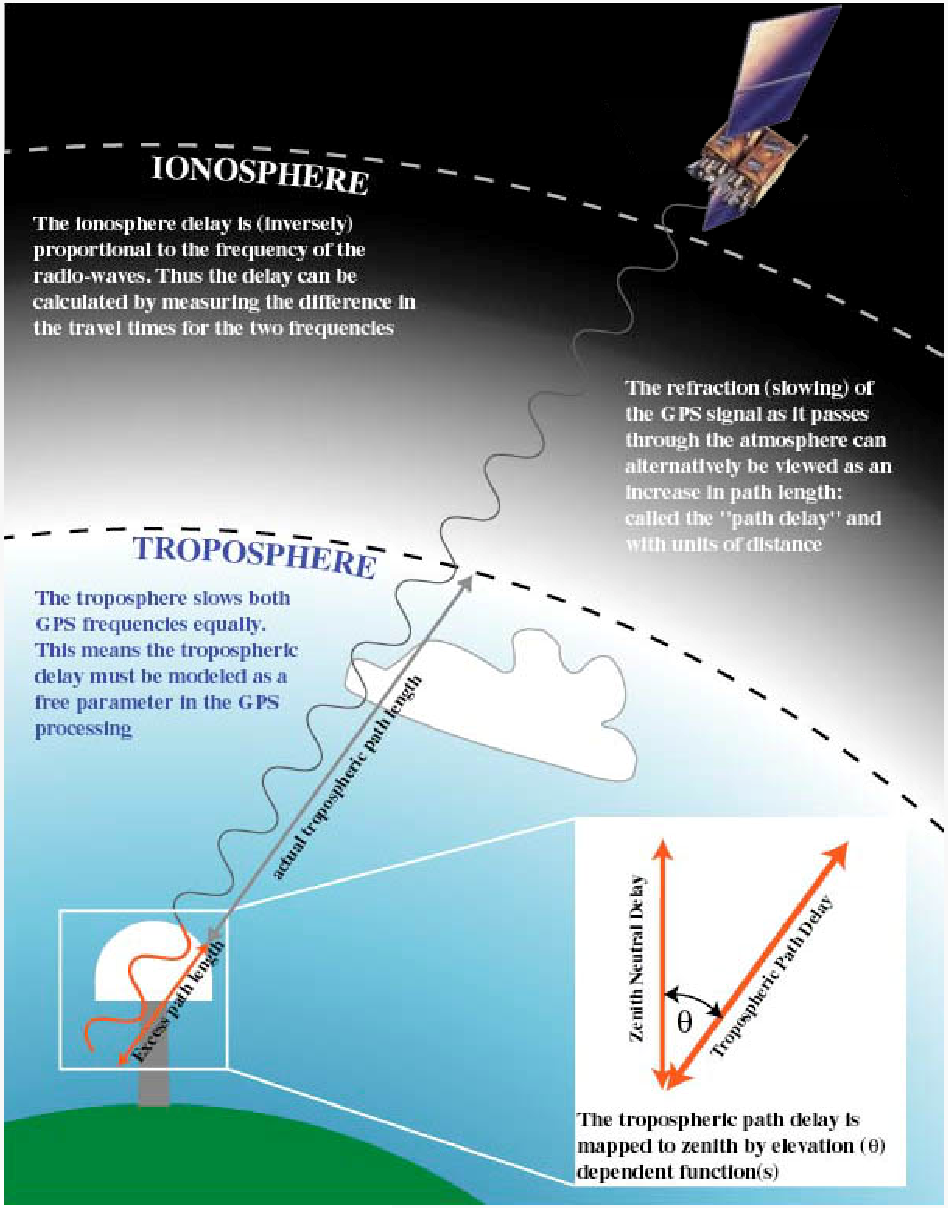
Role of Water Vapor in Weather and Climate

- Water vapor also plays a critical role in the global climate system:
  - the most plentiful greenhouse gas;
  - absorbs and radiates energy from the sun;
  - affects the formation of clouds and aerosols, and the chemistry of the lower atmosphere.

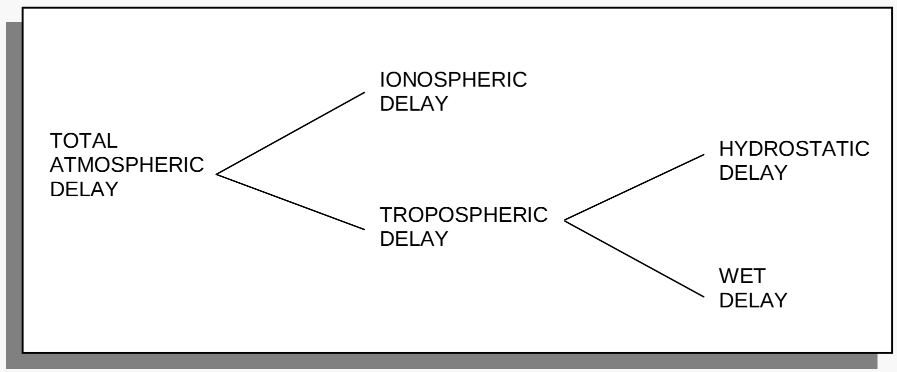
Water Vapor is Difficult to Observe

- Manifests itself only when it changes state.
- Varies greatly over the planet: < 5 mm near the poles and > 50 mm near the equator.
- Most (~ 95%) of the water in the atmosphere resides below 5 km (500 hPa).
- Significant changes in the vertical and horizontal distribution of water vapor can occur rapidly (minutes to hours) during active weather.
- Seasonal changes are linked to global temperature and atmospheric circulation patterns.
- Multi-year changes appear to be linked to the large changes in the sea surface temperature in the tropical Pacific associated with ENSO, the El Niño-Southern Oscillation.

GPS Meteorology

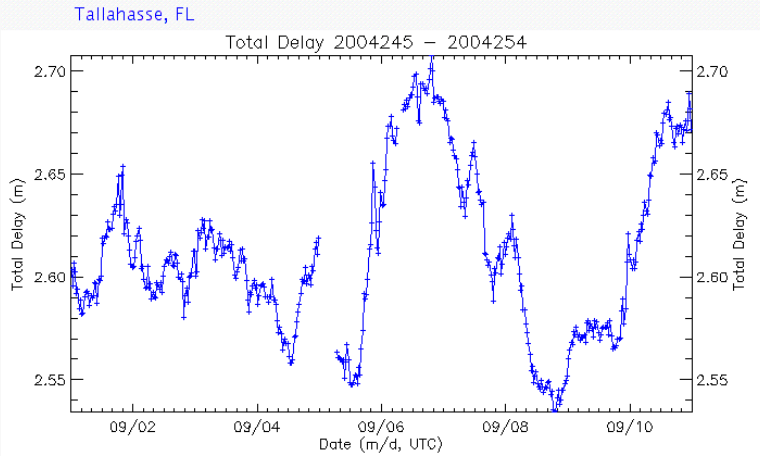


- Signal delays caused by the lower atmosphere (troposphere) primarily have a wet and dry component.
- The dry delay is caused by the mass of the atmosphere, and can be estimated with high accuracy from a surface pressure measurement.
- The wet delay is simply the difference between the total delay and the dry delay.
- The ratio of the wet to dry delay is exactly the water vapor mixing ratio.
- The wet signal delay is nearly proportional to the total quantity of ***precipitable water vapor*** in the atmosphere directly above the GPS site.

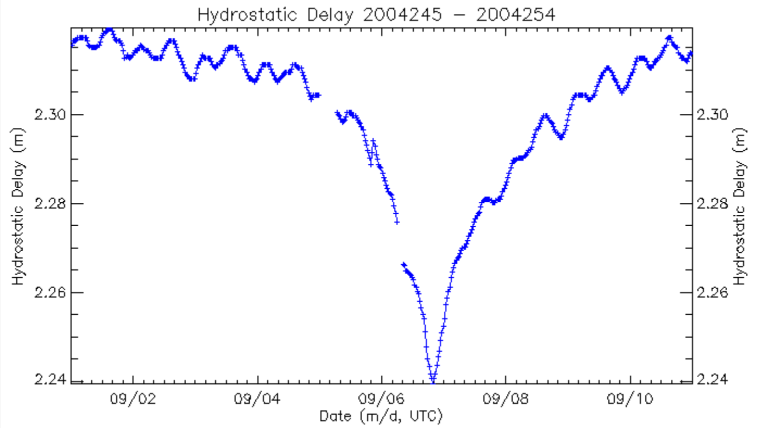


How IPW is Calculated

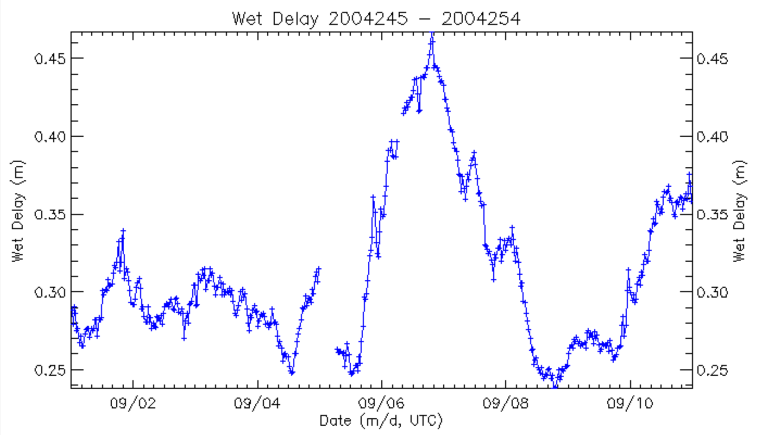
ZTD Measured

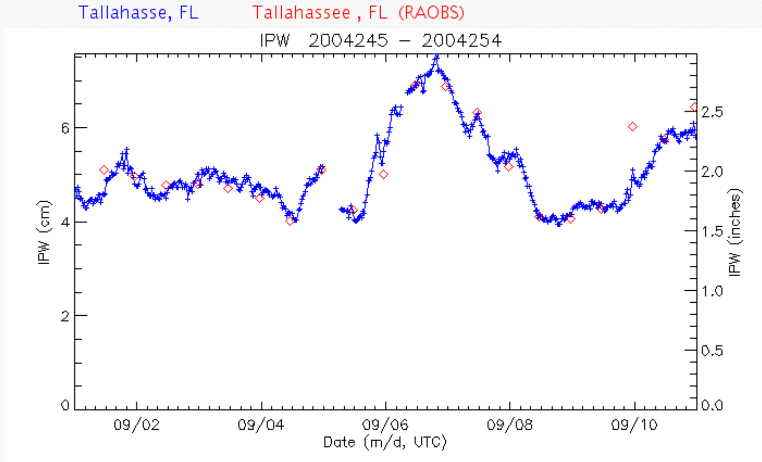


ZHD Computed from Psfc

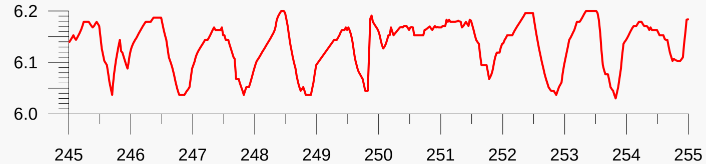


ZWD = ZTD-ZHD

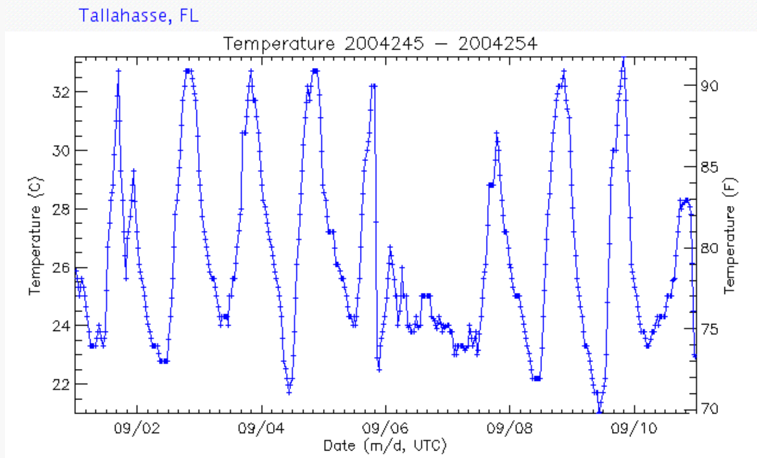




IPW = ZWD x Π

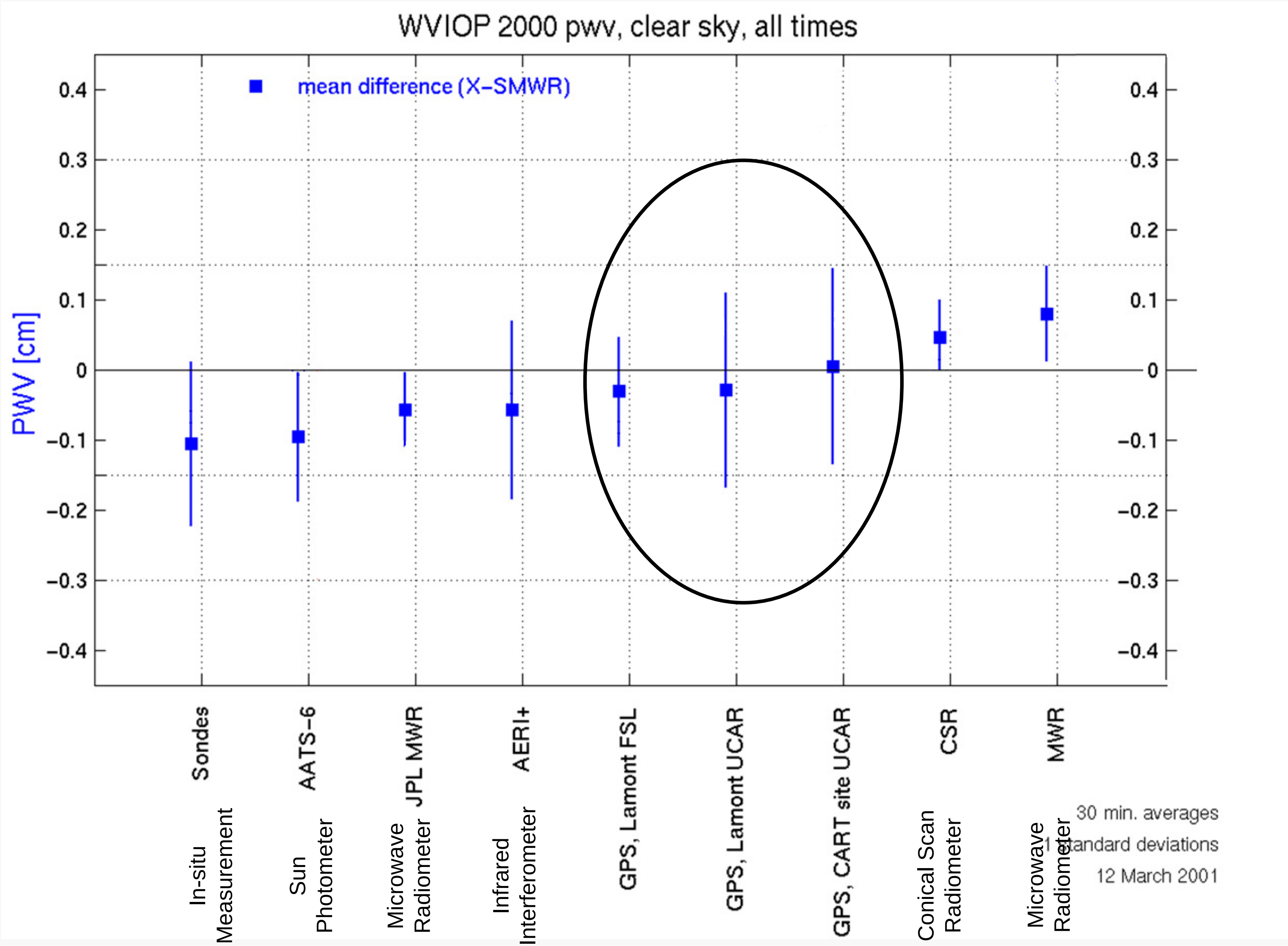


Π



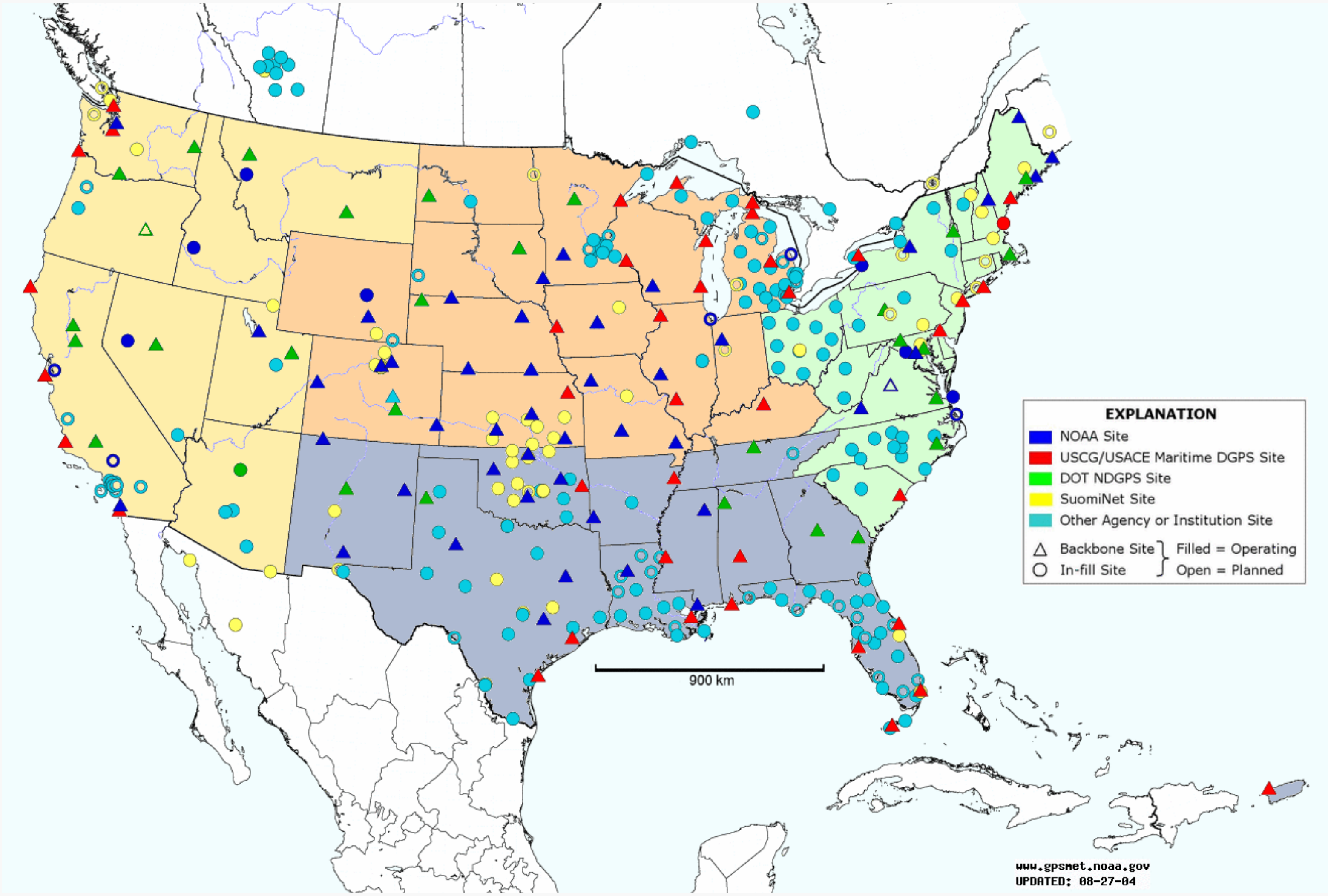
Tm

GPS-IPW Measurement Accuracy



Assimilation into Weather Models

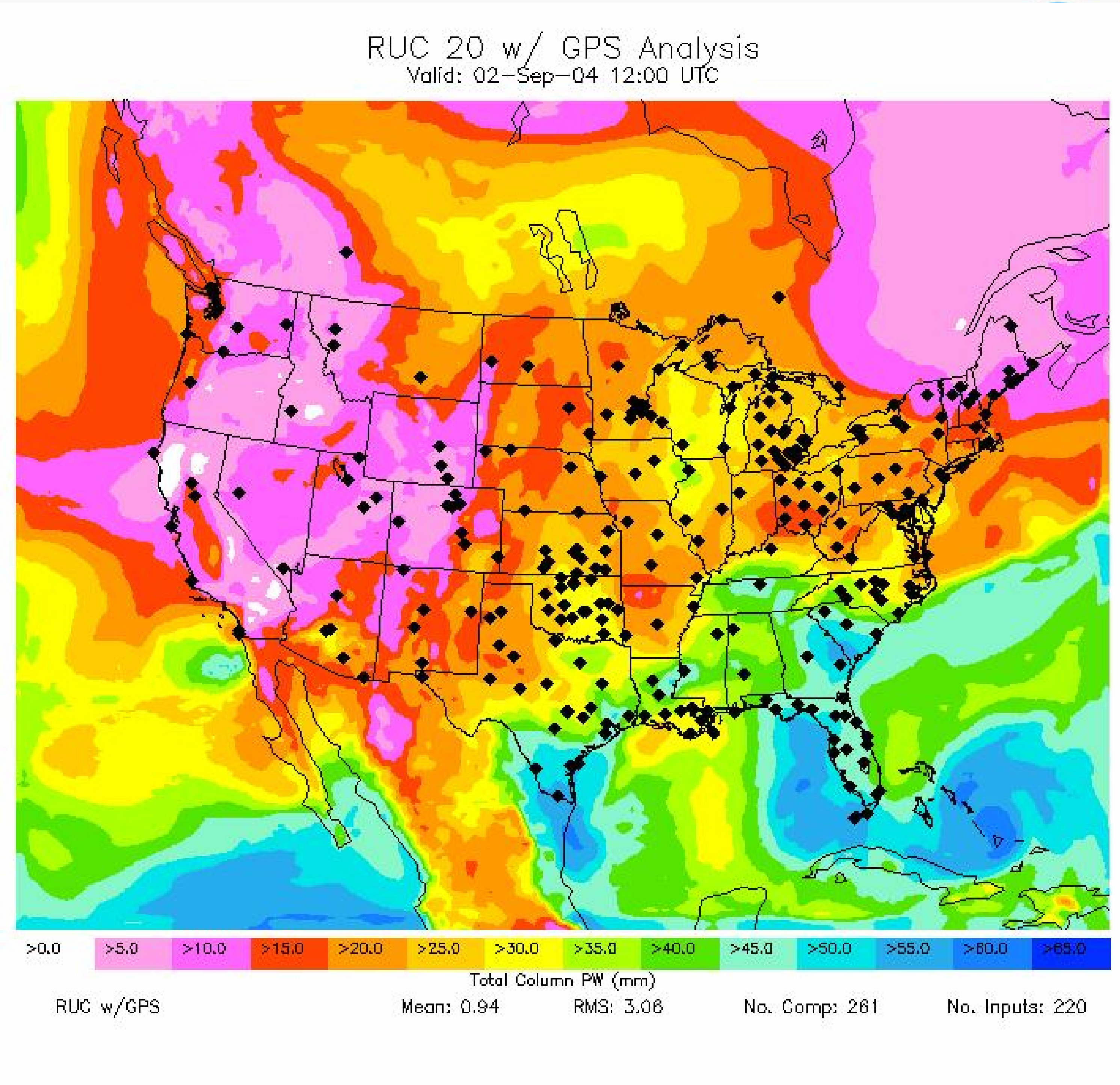
- Data from a network of approximately 300 CORS sites are assimilated hourly into a research version of the Rapid Update Cycle (RUC 20), an operational NWS weather prediction model.



Atmospheric Data Assimilation

- More observations than just GPS go into modern NWP models like the RUC.

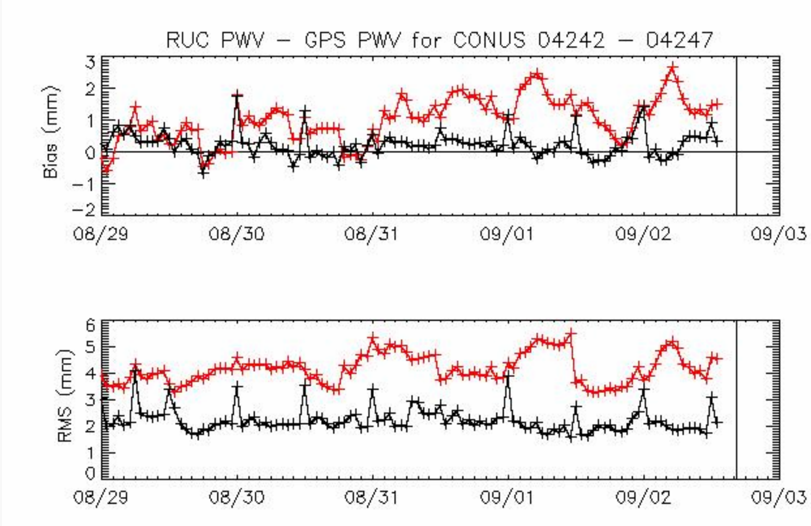
Data Type	~Number	Frequency
Rawinsonde (balloons)	80	/12h
NOAA 404 MHz wind profilers	31	/ 1h
PBL (915 MHz) wind profilers	24	/ 1h
RASS virtual temperatures	10	/ 1h
VAD winds (WSR-88D radars)	110-130	/ 1h
Aircraft (ACARS)	1400-4500	/ 1h
Surface/METAR	1500-1700	/ 1h
Surface/Buoy	100-150	/ 1h
Surface/Mesonet	2500-4000	/ 1h
GOES cloud-drift winds	1000-2500	/ 1h
GOES precipitable water	1500-3000	/ 1h
GPS precipitable water	300	/ 1h
SSM/I precipitable water	1000-4000	/ 6h
GOES cloud-top pressure/temp	10 km res	/ 1h
Ship reports/dropsondes	Point	as available

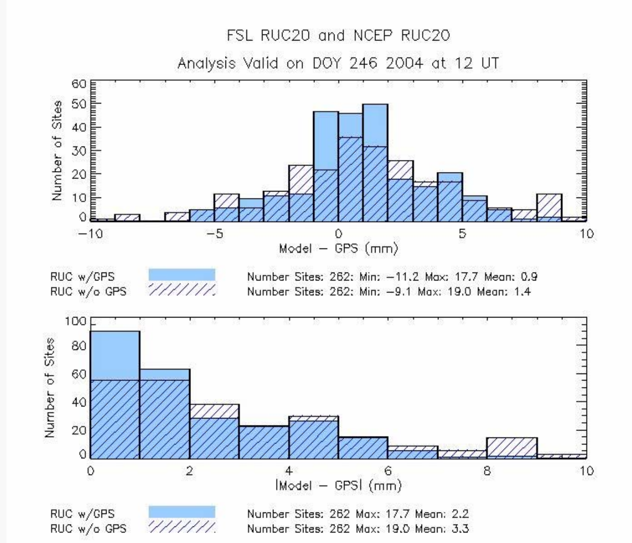


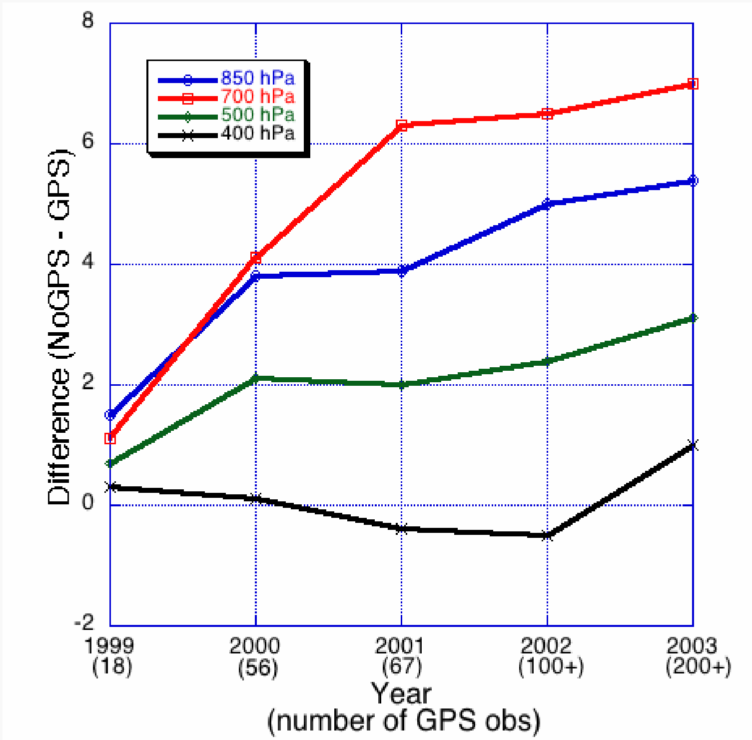
RUC 20 w/ GPS Analysis
Valid: 02-Sep-04 12:00 UTC
>0.0
>5.0
>10.0
>15.0
>20.0
>25.0
>30.0
>35.0
>40.0
>45.0
>50.0
>55.0
>60.0
>65.0
Total Column PW (mm)
RUC w/GPS
Mean: 0.94
RMS: 3.06
No. Comp: 261
No. Inputs: 220

Assimilation of GPS-IPW Improves Weather Forecast Accuracy

FORECAST SYSTEMS LABORATORY
BOULDER, COLORADO



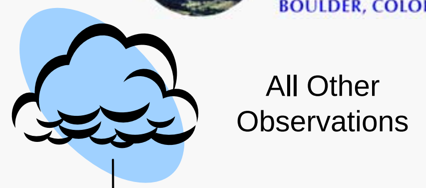


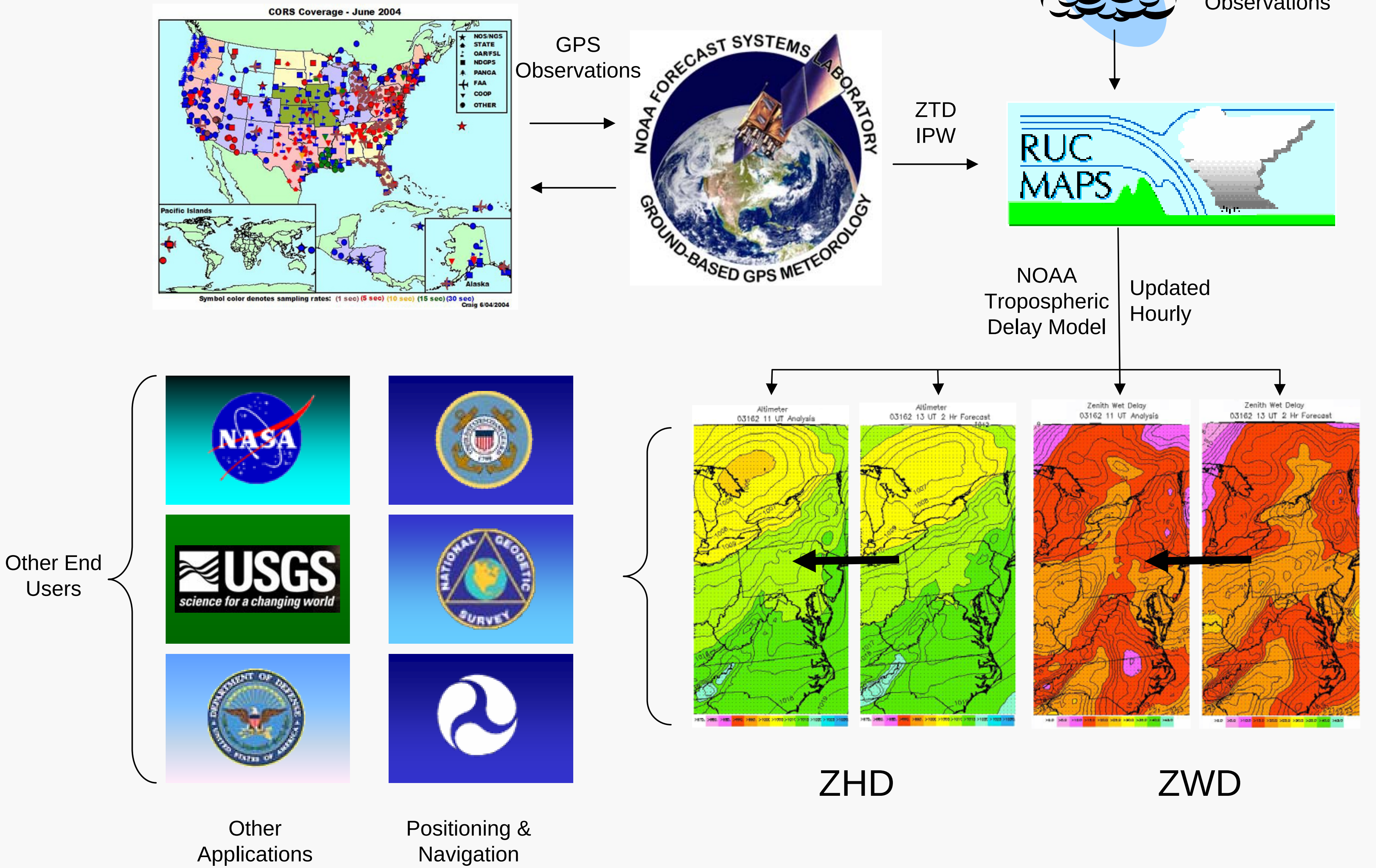


Notes

- Considering the number of different kinds of observations assimilated into modern Wx models, it's surprising we see any positive impact at all!
- Bias & RMS analysis errors (above) are systematically reduced.
- 3-h forecast accuracy (left) improves as network expands.
- Greatest improvement in lower levels where most of the moisture resides.

Tropospheric Signal Delay Models
A GPS-Met Spin-off





Tropospheric Signal Delay Models

- FSL has developed techniques to invert NOAA weather forecast models to provide gridded 2-D descriptions of the zenith tropospheric signal delay over the U.S. and surrounding regions.
- Tools to convert these grids to zenith signal delay at any point are available from FSL and are now being tested at several universities.
- 2 RMSD accuracy appears to be < 5 cm, but this has to be independently tested and verified under all weather conditions.
- The ability to accurately define and remove the effects of ionospheric and tropospheric delays of the GPS signals will have significant impact on numerous civilian and military activities.

Tropospheric Signal Delay Models

- The first and most obvious impact will be on high accuracy GPS positioning and navigation:
  - NRT solution of carrier phase ambiguities leading to centimeter-level accuracy for both single and dual frequency receivers.

- The largest benefits are expected in the measurement of the vertical coordinate since tropospheric errors scale directly into height errors.

- Less time on station for the same level of accuracy = improved productivity in field surveying.

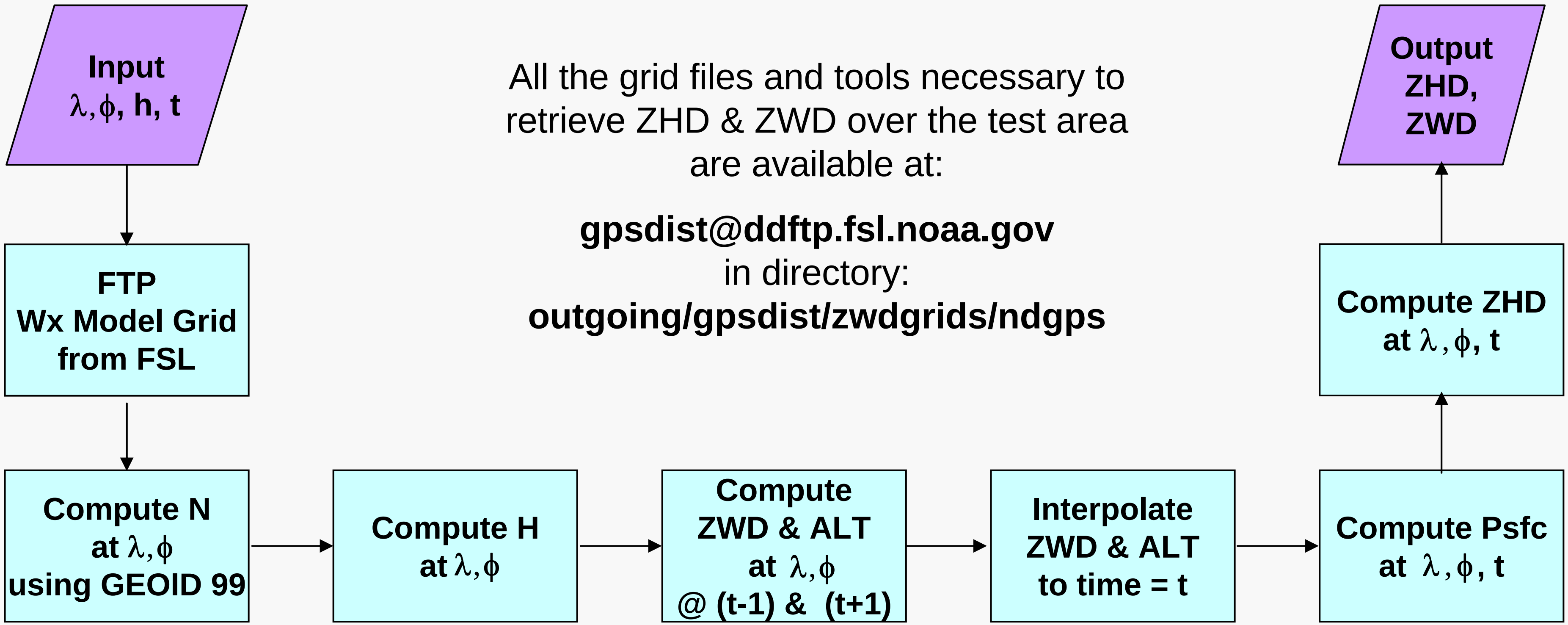
- Other anticipated applications include:
  - correction of InSAR data for improved remote monitoring of changes in elevation with time;
  - using refractivity corrected InSAR data to improve soil moisture estimates;
  - improved radar-derived precipitation estimates.

Generalized Process Flow Diagram

Improved GPS Positioning Using Atmospheric Models

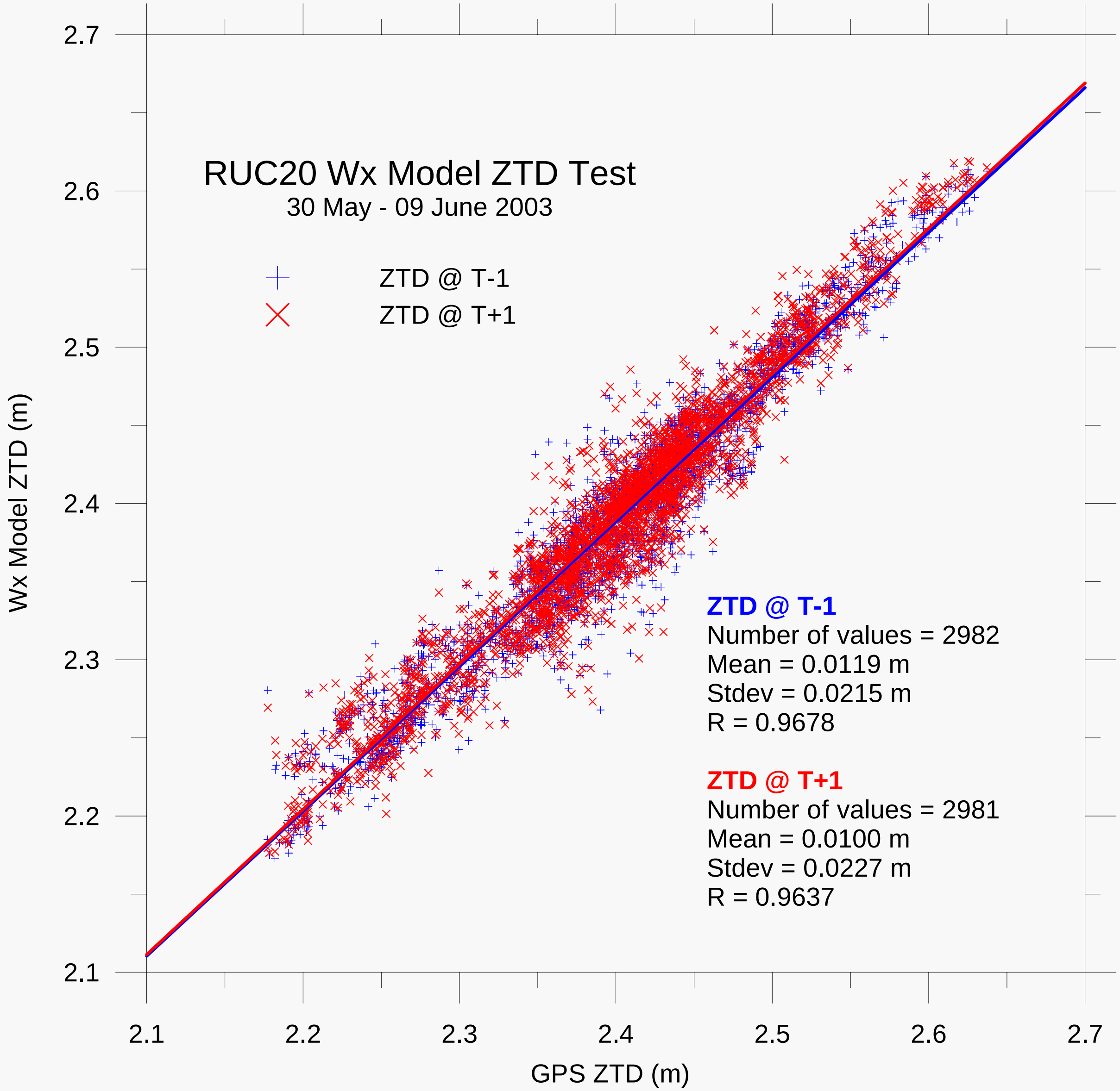
All the grid files and tools necessary to retrieve ZHD & ZWD over the test area are available at:

gpsdist@ddftp.fsl.noaa.gov
in directory:
outgoing/gpsdist/zwdgrids/ndgps

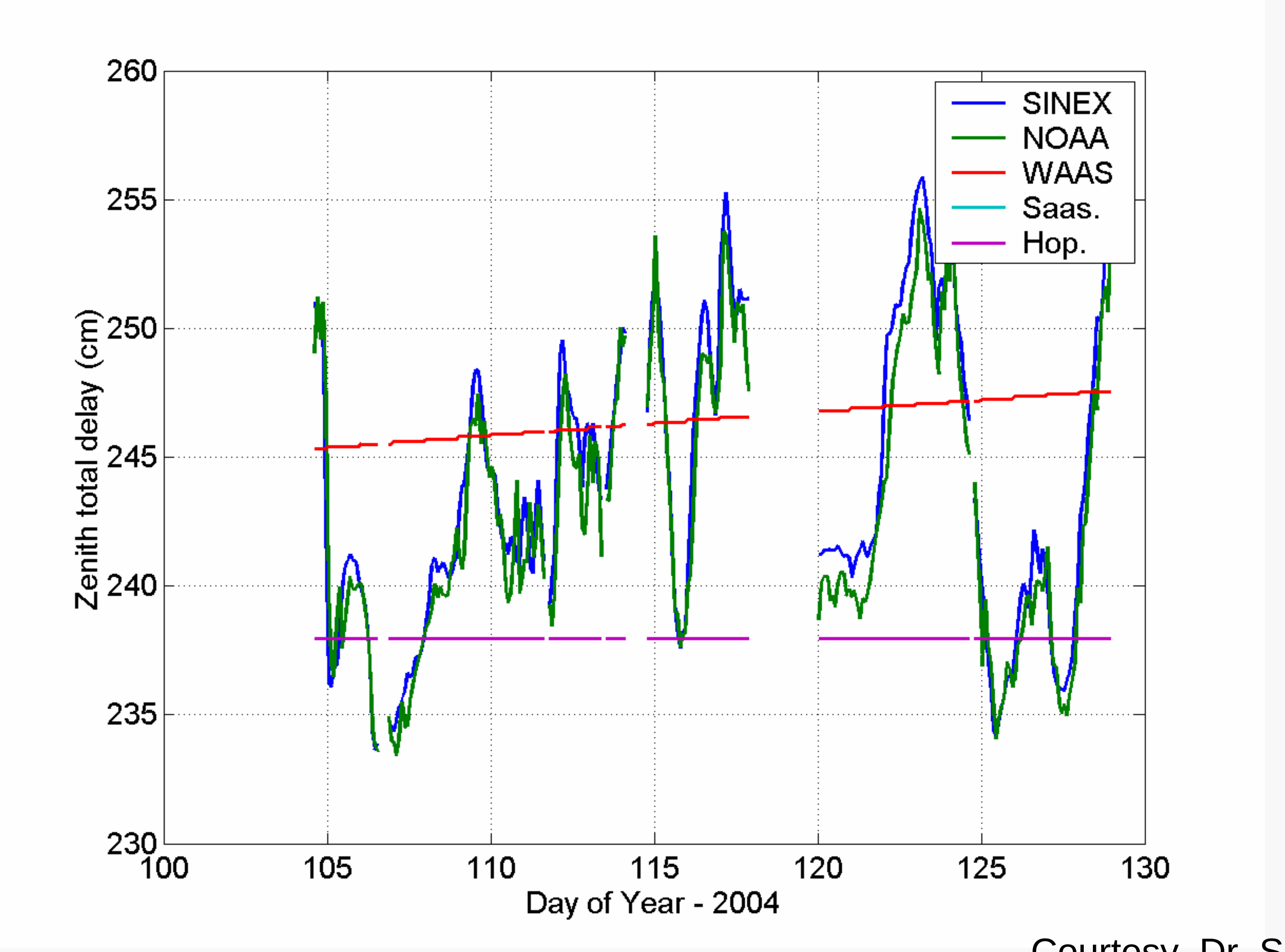


λ = rough latitude
ϕ = rough longitude
h = rough ellipsoidal height
t = time of observation
N = approximate geoidal height
H = approximate orthometric height
ZHD = zenith hydrostatic signal delay (m)
ZWD = zenith wet signal delay (m)

Weather Model Tropospheric Delay Estimation Accuracy

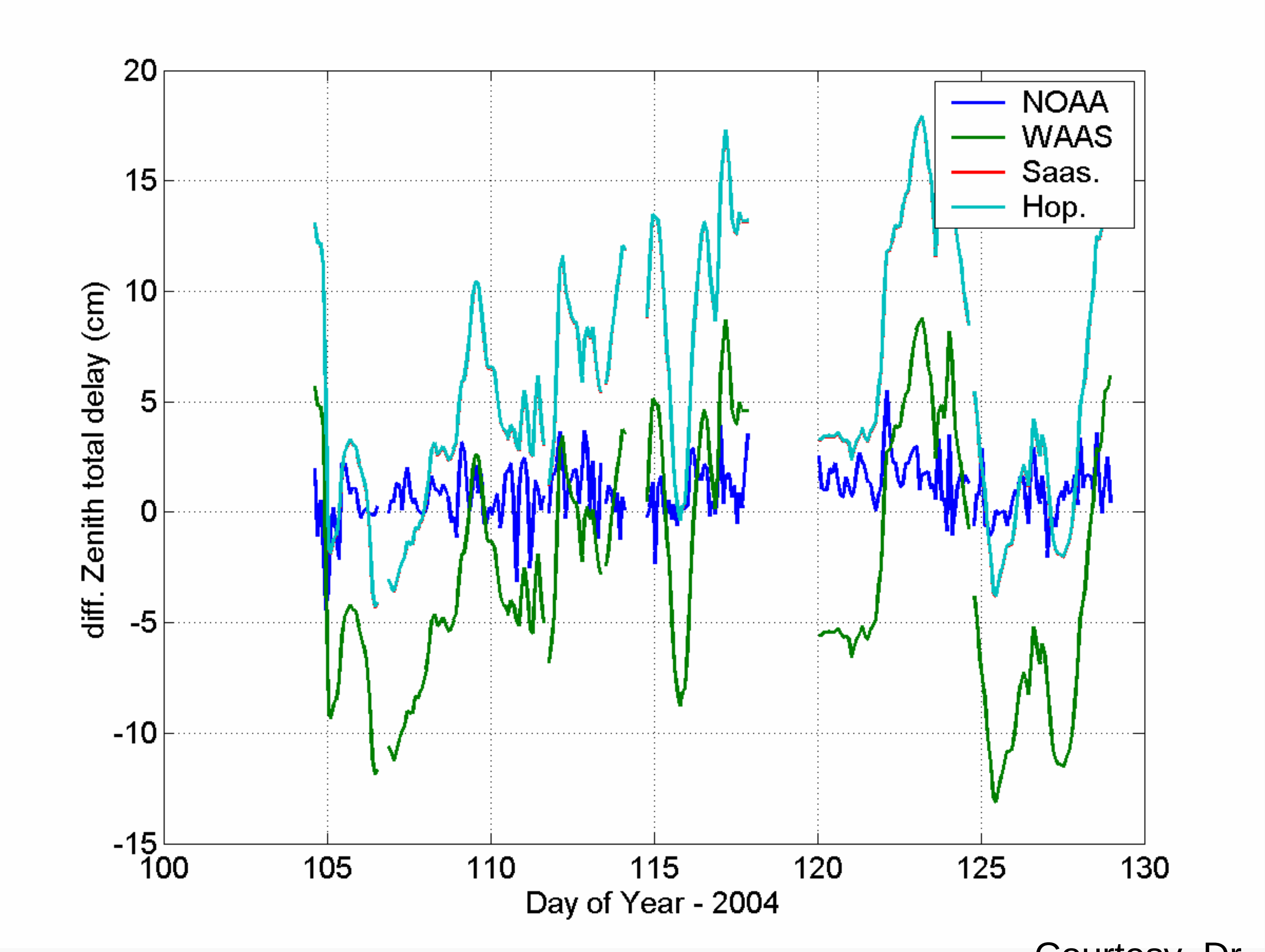


Wx Model-Derived Total Delays Vs Independent Observations



Courtesy, Dr. Sunil Bisnath formally with USM, now at Harvard Smithsonian Astrophysical Observatory

Differences Between Models and Observations



Courtesy, Dr. Sunil Bisnath formally with USM, now at Harvard Smithsonian Astrophysical Observatory

Initial Results are Encouraging

Basic Technique: single reference station approach, a standard tropospheric model and a robust ambiguity float solution approach gives **15 - 25 cm accuracy**.

- 10 to 25% improvement using a multiple reference station approach. > **11 – 23 cm**

- 20 to 25% improvement using a single reference station approach and NOAA tropospheric corrections. > **11 – 20 cm**

- 27 to 40% improvement using a combination of the multiple reference station approach and the NOAA tropospheric corrections. > **9 – 18 cm**

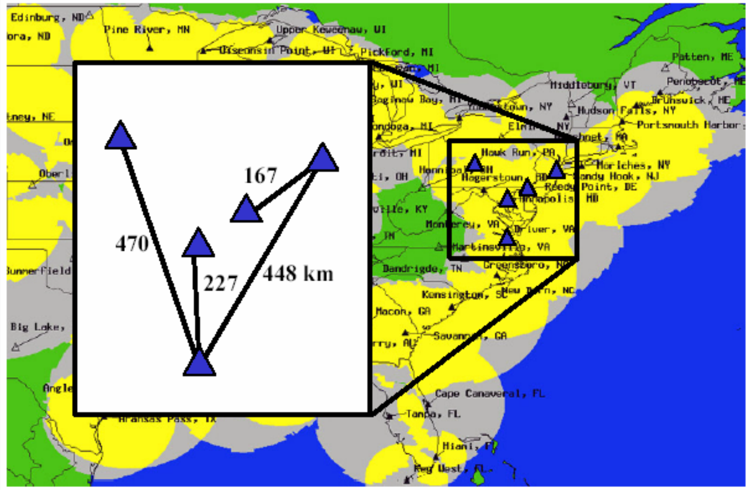


Figure 11: North-Eastern test network

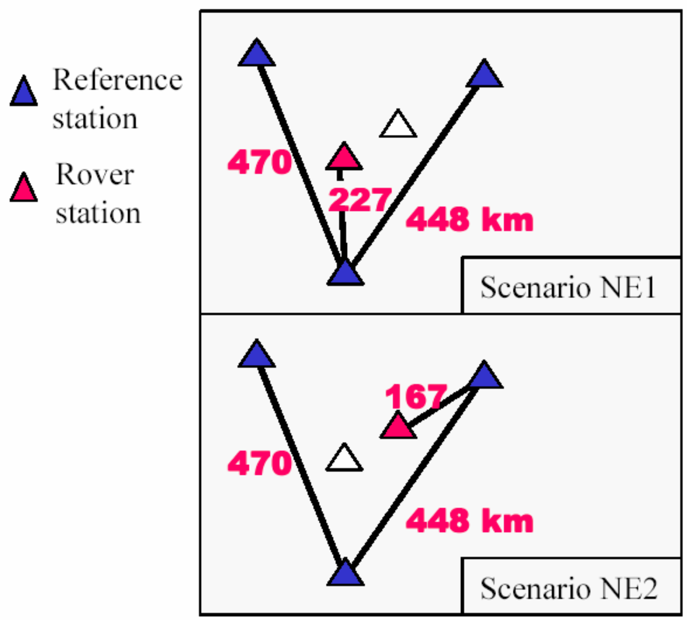


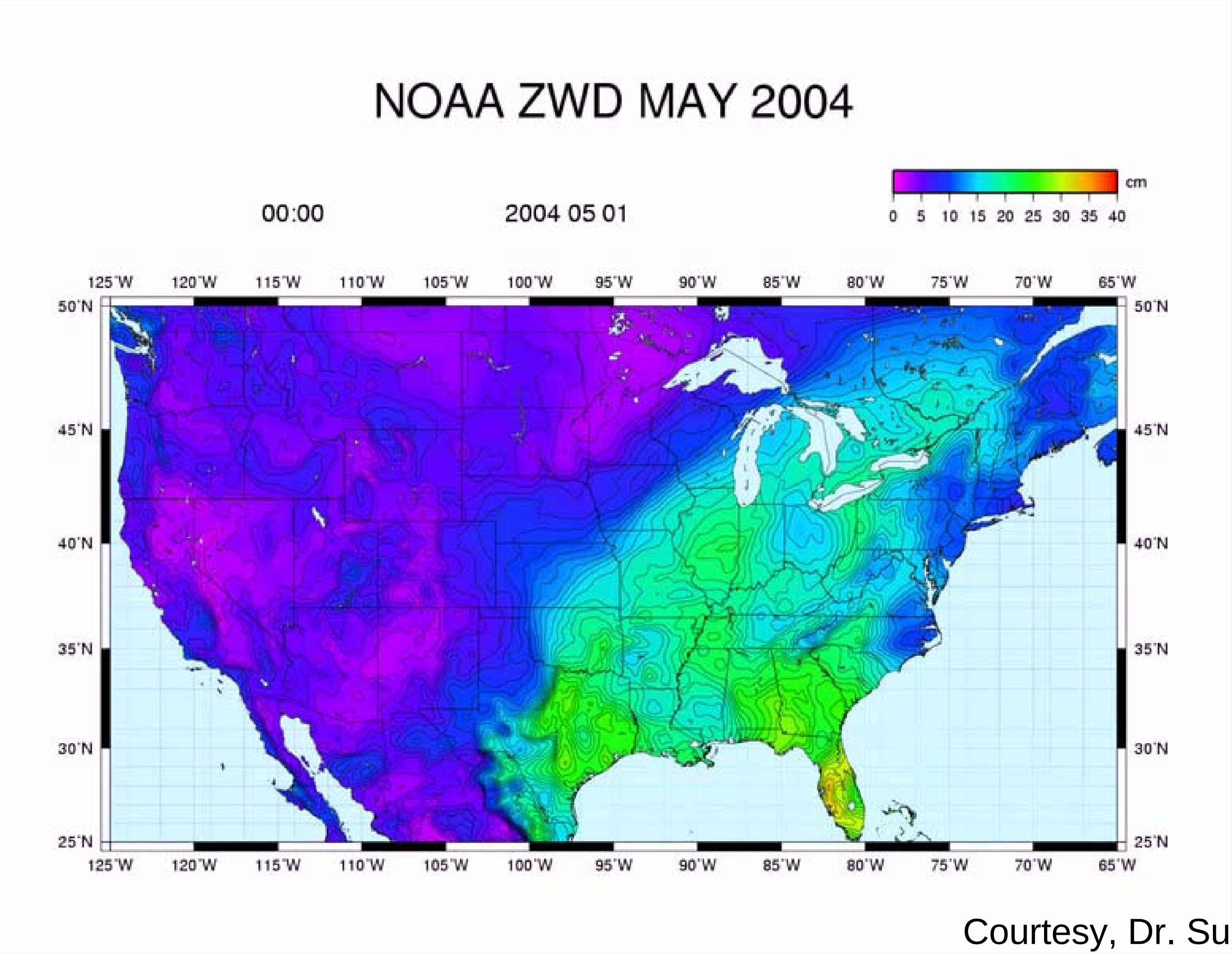
Figure 12: NE1 and NE2 test scenarios

Improvements of USCG RTK Positioning Performance Using External NOAA Tropospheric Corrections Integrated with a Multiple Reference Station Approach

P. Alves, Y.W. Ahn, J. Liu and G. Lachapelle, University of Calgary
D. Wolfe and A. Cleveland, U.S. Coast Guard

Presented at National Technical Meeting, Institute of Navigation, San Diego, 26-28 January 2004

Wx Model-Derived Wet Signal Delay Over CONUS



Courtesy, Dr. Sunil Bisnath formally with USM, now at Harvard Smithsonian Astrophysical Observatory

Questions?

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